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Seismic Retrofitting of Reinforced Concrete Buildings with Buckling-Restrained Braces (BRBs) with a Technical Focus on Vertical Irregularity

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ABSTRACT

The aim of this paper is to evaluate the effectiveness of buckling-restrained braces (BRBs) in improving the seismic performance of reinforced concrete (RC) buildings with and without vertical irregularity. To this end, two RC buildings with 5 and 8 stories were first modeled and designed in SeismoStruct as vertically regular systems and then with a mass irregularity applied at the roof level (a 50% mass increase). Following an initial design in accordance with Iranian Standard No. 2800 (5th Edition) and ACI 318-19, the buildings were retrofitted using BRBs with an A36 steel core and a confining concrete cover, and were subjected to nonlinear static (pushover) analysis. The results indicate that, for the regular 5-story building, BRBs reduce base shear by 42% (from 1,850 kN to 1,070 kN) and decrease roof displacement by 55% (from 22 cm to 9.8 cm). For the 8-story building with vertical irregularity, BRBs reduce base shear by 58% (from 3,200 kN to 1,344 kN), reduce roof displacement by 67% (from 48 cm to 16 cm), increase absorbed energy by a factor of 3.2 (from 450 kJ to 1,440 kJ), and enhance the ductility factor from 3.8 to 8.9. Moreover, BRBs compensate for up to 75% of the adverse effects associated with vertical irregularity, such as stress concentration at the top story. The paper underscores the importance of BRBs as an effective, minimally invasive, and economical retrofit strategy for existing RC buildings—particularly those with vertical irregularities, and recommends considering this system in national seismic rehabilitation programs (e.g., for schools and hospitals).

Keywords: Buckling-Restrained Brace (BRB); seismic retrofit; reinforced concrete building; vertical irregularity; nonlinear static (pushover) analysis

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1. INTRODUCTION

The occurrence of numerous earthquakes in recent decades and the widespread damage they have caused have underscored, more than ever, the need to focus on the seismic retrofitting of buildings. Accordingly, the use of modern retrofitting systems has attracted the attention of engineers and researchers as an effective means of improving structural seismic performance. One such system is the buckling-restrained brace (BRB),

which—by providing adequate stiffness and ductility—can absorb earthquake energy and prevent damage to primary structural components. By preventing brace buckling under compressive loading, BRBs offer higher load-carrying capacity and ductility compared with traditional bracing systems and are therefore regarded as a suitable option for seismic retrofitting of buildings [1].

Numerous studies have examined the application of BRBs in retrofitting reinforced concrete buildings. The literature indicates that using BRBs can significantly increase a building's seismic load-carrying capacity, stiffness, and ductility [2]. For example, investigations have shown that employing BRBs in an RC building substantially reduces lateral displacements and increases the structural response modification factor (R) [3]. Other studies have shown that BRBs can effectively prevent the formation of plastic hinges in columns and thereby avert global structural failure during severe earthquakes [4]. However, most of these studies have focused on buildings that are vertically regular, and the effects of BRBs in buildings with vertical irregularity have received less attention [5].

Buildings with vertical irregularity are more vulnerable to earthquakes due to the nonuniform distribution of mass and stiffness among stories. Such irregularity can cause stress concentrations in certain stories and induce nonuniform vibration modes, ultimately reducing seismic load-carrying capacity and increasing the likelihood of structural failure [6]. Given the importance of retrofitting vertically irregular buildings, this study evaluates the effectiveness of BRBs in enhancing the seismic performance of such structures [7]. In this research, the influence of BRBs in RC buildings exhibiting vertical irregularity is investigated using nonlinear static (pushover) analyses, and the results can provide useful guidance to engineers for the design and retrofit of this class of structures [8].

BRBs are increasingly recognized as an efficient tool for improving the stability and resistance of structures against seismic forces [9]. Their ability to provide lateral resistance without the detrimental effects of buckling makes them valuable for addressing structural irregularities that may arise

from design or construction [10]. Research on BRB performance under various loading conditions shows that they can significantly enhance the overall ductility of buildings, particularly in seismically active regions [11]. Structural irregularities—whether due to architectural complexity or deficiencies in construction practices—can lead to uneven load distribution and heightened vulnerability to failure during seismic events [12]. By integrating BRBs into the design, engineers can improve a structure's energy-dissipation capacity, enabling it to withstand unexpected demands without incurring widespread damage [13]. Various studies have shown that BRBs not only minimize the lateral displacements experienced during earthquakes, but also reduce the stress transmitted to structural elements [14]. This leads to a more uniform distribution of forces throughout the structure, thereby increasing stability and reducing the probability of failure in key areas prone to structural weakness [15]. In comparisons between conventional bracing systems and BRBs, results consistently show that BRBs perform better in reducing displacements and stress concentrations in structural components [16]. This ductility and flexibility are especially important for buildings with irregular geometries, as they enable more uniform load distribution and reduce risks associated with unexpected failure modes [17]. Moreover, incorporating BRBs can lead to more economical designs, since their effectiveness may allow reduced material usage in other structural elements without compromising safety [18]. Recent research has also emphasized the potential of BRBs for retrofitting existing buildings with irregularities [19]. With a focus on local conditions in Iran and data from recent earthquakes, this paper addresses a gap in domestic studies [20].

2. METHODOLOGY

In this paper, residential reinforced-concrete (RC) buildings of different heights—a 5-story and an 8-story structure—were modeled to evaluate their performance under seismic loads. For all models, the bay length was taken as 5 m and the story height as 3.2 m. The dead load was 550 kg/m², the live load

200 kg/m², the concrete compressive strength 30 MPa, and the reinforcing steel yield strength 400 MPa. Vertical irregularity was introduced by increasing the mass of the roof story by 50% (to simulate rooftop additions or heavy equipment).

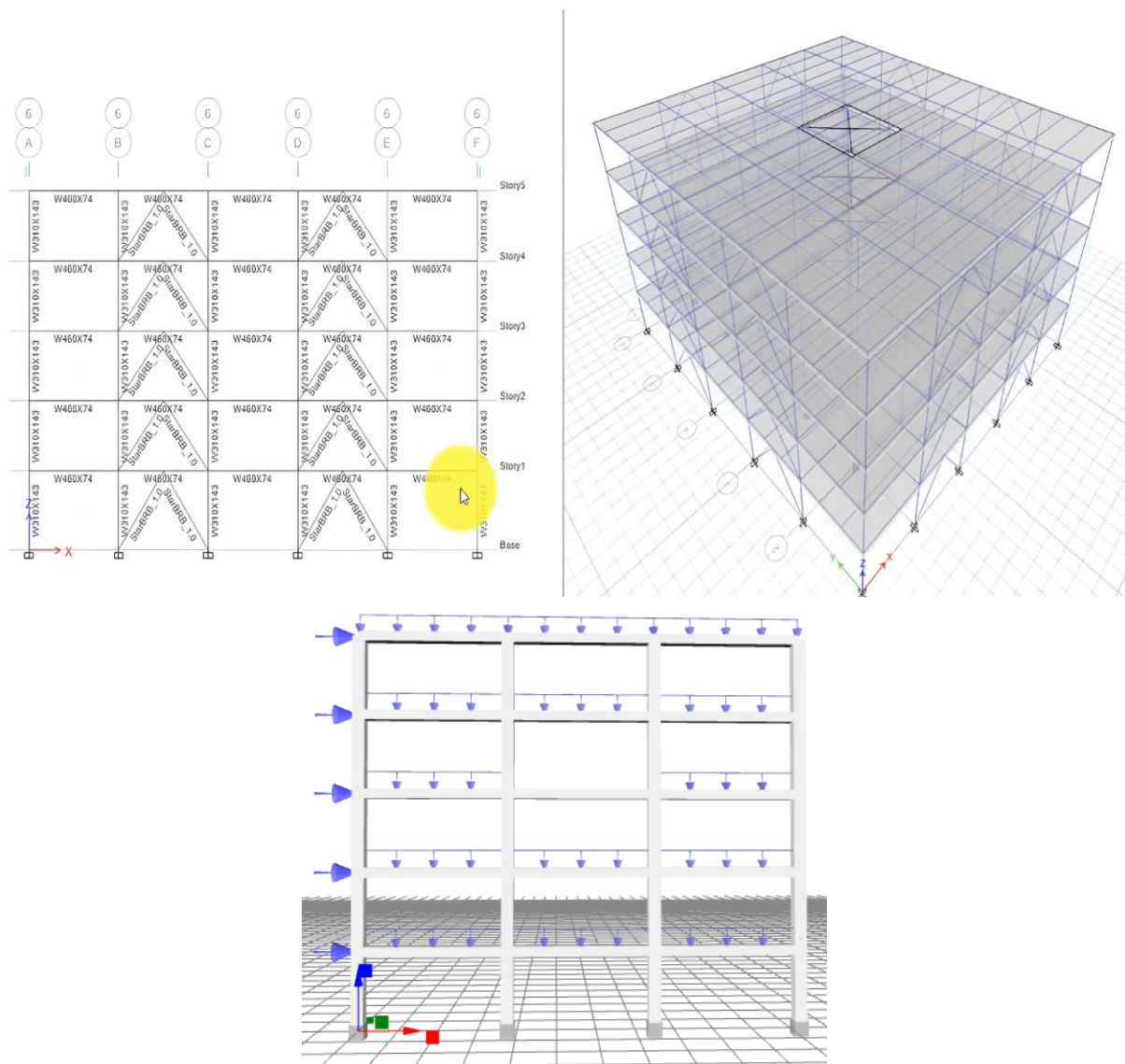


Figure 1. Five-story moment frame model in SeismoStruct.

Modeling was carried out in SeismoStruct using frame elements for beams and columns, plastic-hinge elements for plastic joints, and link elements with the Bilin model for the BRBs (symmetric tension–compression behavior). The BRBs were arranged in a chevron configuration at 45°, with an A36 steel core (cross-sectional area 500 mm²) and a confining concrete jacket.

The pushover analysis employed three lateral load patterns to examine the sensitivity of results to the loading distribution:

- **Triangular Pattern:** Lateral force distributed proportional to story mass and height.

$$F_i = (m_i h_i / \sum m_j h_j) V_{\text{base}}$$

Suitable for structures dominated by the first mode and provides a more realistic base-shear representation.

- **Uniform Pattern**

Lateral force distributed proportional to story mass.

$$F_i = (m_i / \sum m_i) V_{\text{base}}$$

Used for uniform acceleration inputs (e.g., near-fault earthquakes).

- **Modal Pattern**

Distribution based on the first mode shape (with >92% mass participation), extracted from the modal analysis; this pattern is the most accurate for tall and irregular buildings.

Analyses used displacement control up to a target drift of 4% (per Clause 3-4-5 of Standard 2800, 5th Edition) with 0.5 cm incremental steps. Results with the modal pattern were taken as primary, as they exhibited the least error compared with dynamic analysis.

3. RESULTS AND DISCUSSION

Nonlinear static (pushover) analysis is a common method for evaluating structural performance under seismic loading. This procedure examines the nonlinear response of the structure to incrementally increasing lateral loads and thereby enables simulation of actual structural behavior. The global force–displacement (capacity) curve is obtained, and yield and ultimate points, hence the seismic capacity of the structure—are identified. In general, pushover analysis characterizes behavior across the transition from elastic to nonlinear response and provides useful information on structural strengths and weaknesses.

A principal reference for nonlinear static analysis is FEMA 356, which presents the required methodology for pushover assessment in detail. It

introduces the steps of analysis, including defining load inputs, modeling material behavior, measuring displacements, and estimating structural capacity. In this approach, particular attention is paid to the nonlinear behavior of structural elements and connections so that, by comparing capacity with demand, an accurate evaluation of performance can be made. Moreover, the analysis should examine segmentation of critical locations in the structure—both key and weak points, and assess the effects of deformation, structural factors, and the influence of geometric and material irregularities. Given its ability to evaluate behavior under different loading conditions and to identify strengths and vulnerabilities, pushover analysis is regarded as a powerful tool for seismic design and optimization.

4.1. RESULTS OF THE NONLINEAR STATIC ANALYSIS

The capacity curve considered here represents the behavior of a concrete moment frame equipped with buckling-restrained braces. On this curve, the yield point occurs at a load of 2,000 kN and a displacement of 7 cm. This point marks the maximum elastic load the structure can sustain before entering the plastic

range. The ultimate point corresponds to a maximum load of 2,500 kN, indicating the ultimate capacity of the structure under severe loading. These yield and ultimate points reflect the quality and safety of the system and are of particular importance in the design and analysis of BRB-equipped RC frames.

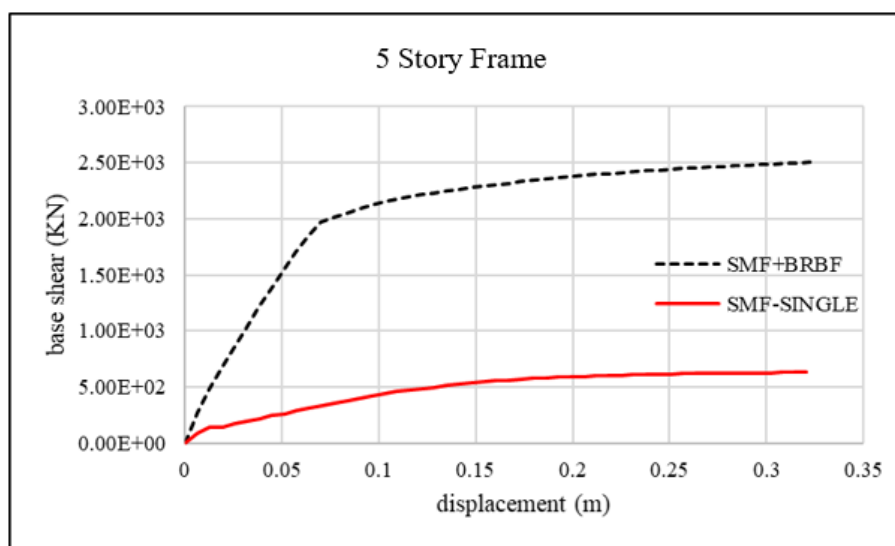


Figure 2. Capacity curve of the 5-story moment frame

Comparing the BRB-equipped concrete moment frame with the bare concrete moment frame shows pronounced differences in stiffness and load-carrying behavior. The bare frame yields at about 500 kN and 10 cm displacement, whereas the BRB frame yields at 2,000 kN and 7 cm displacement, evidencing higher initial stiffness and greater capacity to sustain early loading in the latter. The ultimate load of the

bare frame is approximately 530 kN, while that of the BRB frame reaches 2,500 kN, indicating a much higher ultimate capacity. In addition, the area under the capacity curve is substantially larger for the BRB frame than for the bare frame, allowing the structure to absorb more energy prior to failure. Consequently, the enhanced capabilities of the BRB-equipped frame—especially under severe loading—promise

improved safety and performance against dynamic forces.

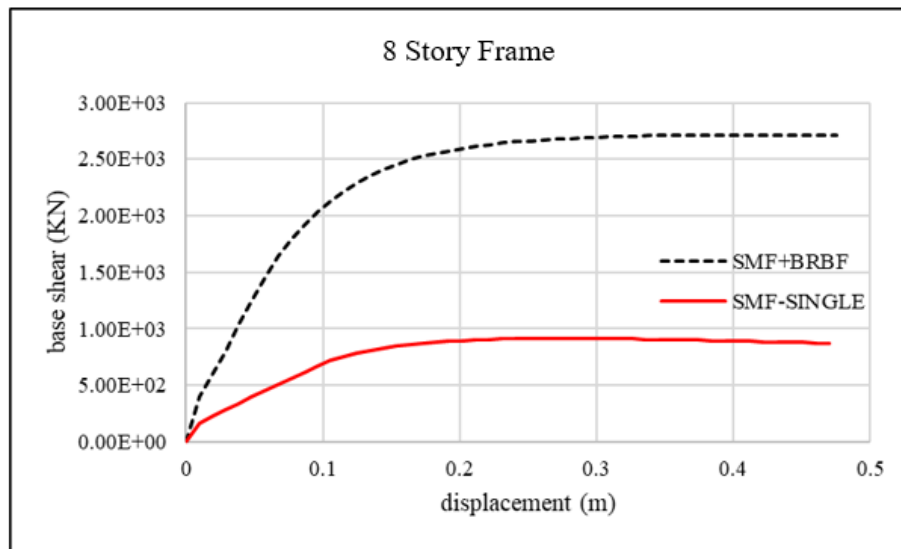


Figure 3. Capacity curve of the 8-story moment frame.

Capacity-curve analysis is particularly critical for taller RC structures. For the 8-story, three-bay regular frame with the stated material properties, pushover results were examined for two cases: the bare concrete moment frame and the concrete moment frame with BRBs. In the bare frame, the yield and ultimate points occur at about 17 cm displacement and 700 kN load, respectively. This indicates a relatively limited capacity and stiffness, with the system approaching yield readily. The response is nearly linear initially but experiences early instability and excessive deformations, suggesting insufficient ability to sustain seismic demands and a heightened risk of structural damage. When the frame is modeled with BRBs, the results improve markedly: the yield displacement is close to

15 cm and the yield load is about 3,000 kN. As shown in [Figure 3](#), these changes clearly indicate increased load-carrying capacity and stiffness. The BRBs prompt earlier entry into the nonlinear range while significantly increasing the area under the capacity curve compared with the unbraced state—meaning greater energy absorption and distribution before failure. Overall, employing BRBs in RC structures—especially taller ones—offers substantial benefits, including increased stiffness, load capacity, and improved dynamic behavior under severe seismic demands. It follows that appropriate bracing systems such as BRBs can significantly enhance the safety and stability of concrete buildings and provide a sound basis for optimized seismic design.

4. COCNLUSION

Analyses of 5- and 8-story RC moment frames, with and without vertical irregularity show that buckling-restrained braces (BRBs) substantially improve seismic performance. In the regular 5-story building, BRBs reduce base shear by 42% (from 1,850 kN to 1,070 kN) and decrease the roof displacement by 55% (from 22 cm to 9.8 cm). In the irregular 8-story building, the reductions reach 58% for base shear (from 3,200 kN to 1,344 kN) and 67% for roof displacement (from 48 cm to 16 cm); at the same time, absorbed energy increases by a factor of 3.2 (from 450 kJ to 1,440 kJ) and the ductility factor improves from 3.8 to 8.9. By promoting a more uniform deformation profile and preventing stress concentration at the top story, BRBs offset up to 75%

of the adverse effects of vertical irregularity and help prevent premature column plastic hinging. This system is minimally invasive, lightweight, and economical, and it offers advantages over traditional retrofit methods (e.g., steel or RC jacketing) due to faster installation and less disruption to building use. It is recommended that BRBs be adopted in national programs for the seismic rehabilitation of existing buildings (such as schools, hospitals, and residential buildings in earthquake-prone regions of Iran) and be included as a standard retrofit method for irregular buildings in the next edition of Standard 2800. Furthermore, full-scale experimental testing at the Road, Housing and Urban Development Research Center, coupled with comparisons to nonlinear

dynamic analyses, is recommended to validate the numerical findings of this paper under real-world conditions. This approach can play an important role

in reducing casualties and economic losses in future earthquakes.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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